Linear line polarimetry modelling of pre-main sequence stars

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Abstract. We present emission line polarimetry data and modelling relevant to the circumstellar geometry and kinematics around pre-main sequence stars. For a sample of both Herbig Ae/Be stars and T Tauri stars, we find that most show polarization changes across Hα, implying that flattened structures are common on the smallest scales – and over a range of stellar masses. We also present Monte Carlo calculations of spectral line profiles scattered in rotating accretion disks. We consider both the case of a central star that emits line photons uniformly, as well as via hot spots. Intriguingly, the switch between a uniform point source and a finite-sized star results in a marked difference in the position angle variation across the line. Our models demonstrate the diagnostic potential of line polarimetry in determining the disk inclination and the size of the inner hole – a spatial scale no other technique currently accesses.

1. General Introduction

It is believed that low-mass stars form through the collapse of an interstellar cloud. During the subsequent pre-main sequence (PMS) T Tauri phase material is accreting from the disk onto the star, most likely through magnetospheric funnels (e.g. Johns-Krull et al. 1999). Whilst this basic picture of star formation is relatively well understood, problems relating to a star's angular momentum remain, as we have little information on the size of the disk inner hole. For intermediate mass (2 – 10 $M_\odot$) Herbig Ae/Be stars our knowledge becomes even more patchy, and for stars above 10 $M_\odot$ there is not even any consensus on the mode of star formation itself.

Traditionally, the switch between low-mass and high-mass star formation has been thought to occur at the T Tauri/Herbig boundary (at $\simeq 2$ M$_\odot$), since this is where low-mass T Tauri stars possess convective envelopes, whilst intermediate mass Herbig Ae star envelopes are radiative. However, recent data indicate that such a division is no longer tenable: Herbig Ae stars and T Tauri stars have a range of characteristics in common, varying from the presence of inverse P Cygni profiles, indicative of active accretion (Catala et al. 1999), to the detections of line polarizations, signalling rotating accretion disks (Vink et al. 2002, 2003). It is clear that what is needed to understand star formation as a function of mass (and ultimately understand the IMF) is observations of the

near-star environment over a wide range of young stellar objects. Polarimetry across emission lines is just such a tool.

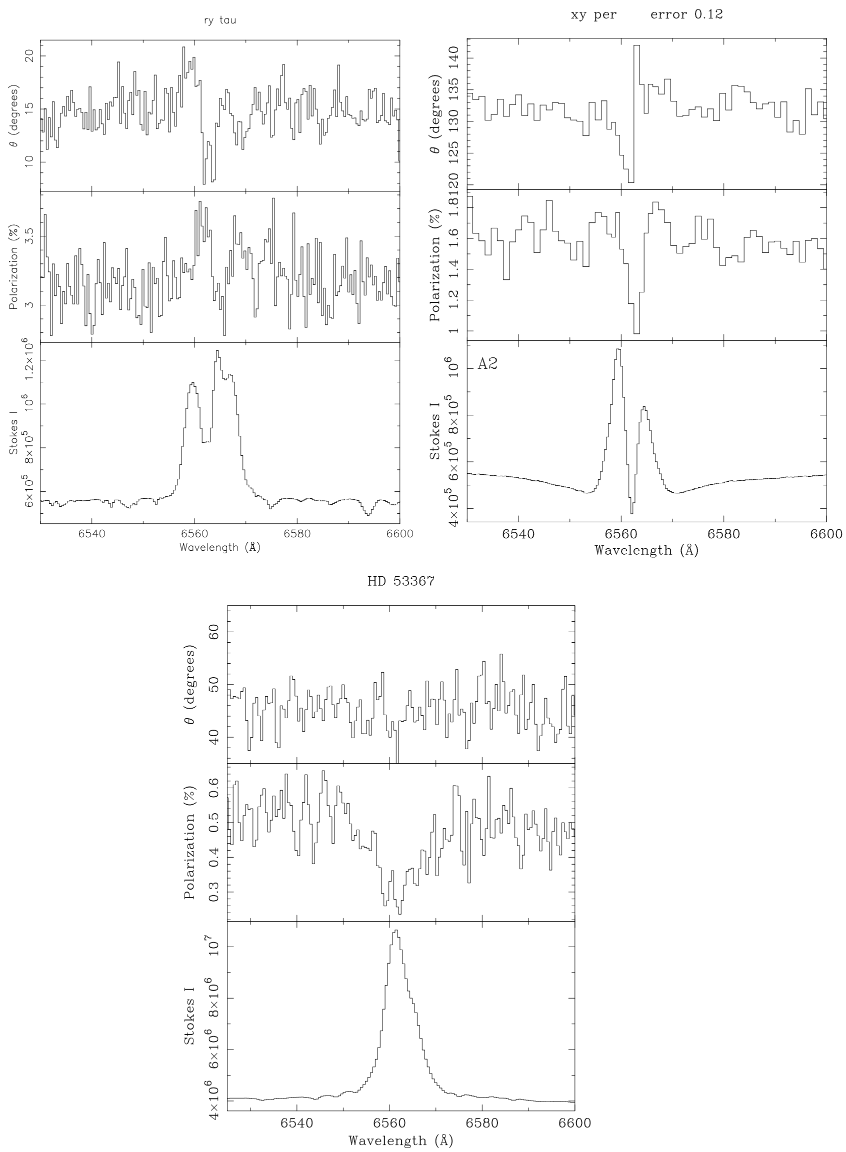

Figure 1. Triplots of the observed polarization spectra of (a) the T Tauri star RY Tau (Vink et al. 2003), the Herbig Ae star XY Per (Vink et al. 2002), and the Herbig Be star HD 53367 (Oudmaijer & Drew 1999). In all plots, the Stokes I spectrum is shown in the lowest panel, the %Pol is indicated in the middle panel, whilst the position angle, θ, is plotted in the upper panel.

2. Line polarimetry

Spectropolarimetry is a powerful tool to study the near-star regions of PMS stars and to determine their geometries. The technique has widely been applied to

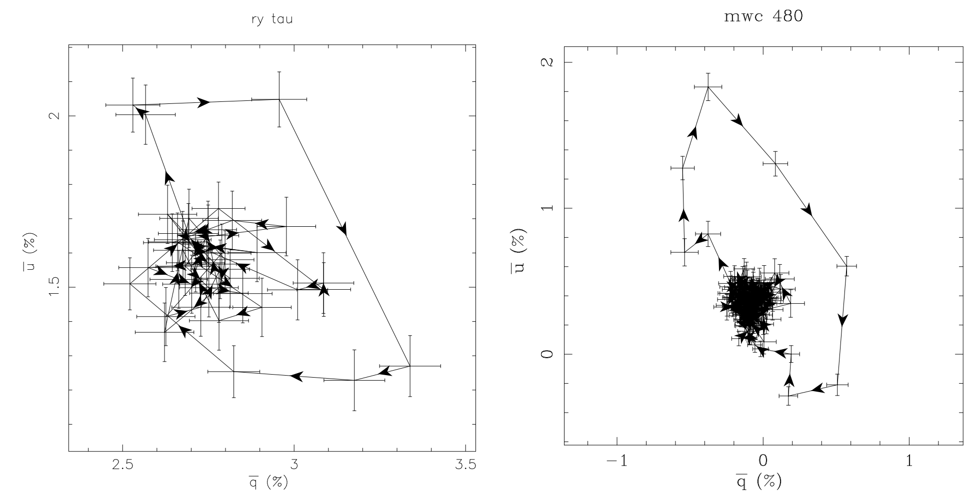

Figure 2. *QU* representations of the observed polarization spectra of the T Tauri star RY Tau and the Herbig Ae star MWC 480. The arrow denotes the sense of increasing wavelength. Note the resemblance in the loops between the Herbig Ae and T Tauri star in the *QU* diagram.

early-type stars, where circumstellar free electrons – e.g. in a disk – are able to polarize the continuum light more than the line photons. This is widely known as 'depolarization' (see Fig. 1(c) and Oudmaijer; these proceedings). In this case, the polarization angle (PA) of the polarization does not change across the line (if it is corrected for foreground), and the shape of the phenomenon in the *QU* plane simply involves a straight line (independent of foreground).

In certain circumstances it is feasible that the *line* photons are scattered and polarized themselves (e.g. McLean 1979). Wood et al. (1993) performed an analytical study of the polarization and PA of a uniform point source that is scattered within a surrounding moving medium. Specifically, for a rotating disk, they found that the PA is no longer constant through the line, but rotates by a few degrees, resulting in a 'loop' in the *QU* plane (see Fig. 2 for examples), which they attributed to stellar occultation. The diagnostic value of this PA flip (*QU* loop) is that it is the direct signpost for the presence of rotation.

3. Data of T Tauri and Herbig Ae/Be stars

In recent years, we have surveyed T Tauri and Herbig Ae/Be stars spectropolarimetrically. For Herbig Be stars, the frequency of depolarizations was found to be essentially the same as was found for classical Be stars in the 1970s – indicating they are embedded in electron scattering disks (see Fig. 1(c) for the Herbig Be star HD 53367 and Oudmaijer, these proceedings).

When observing later spectral type PMS stars, one might perhaps expect to witness a sharp decrease in the number of polarization line effects, because the amount of free electrons is anticipated to drop. Furthermore, narrow-band filter work in the 1980s indicated a general absence of polarization changes across Hα in T Tauri stars (e.g. Bastien 1982). However, this is not the case when

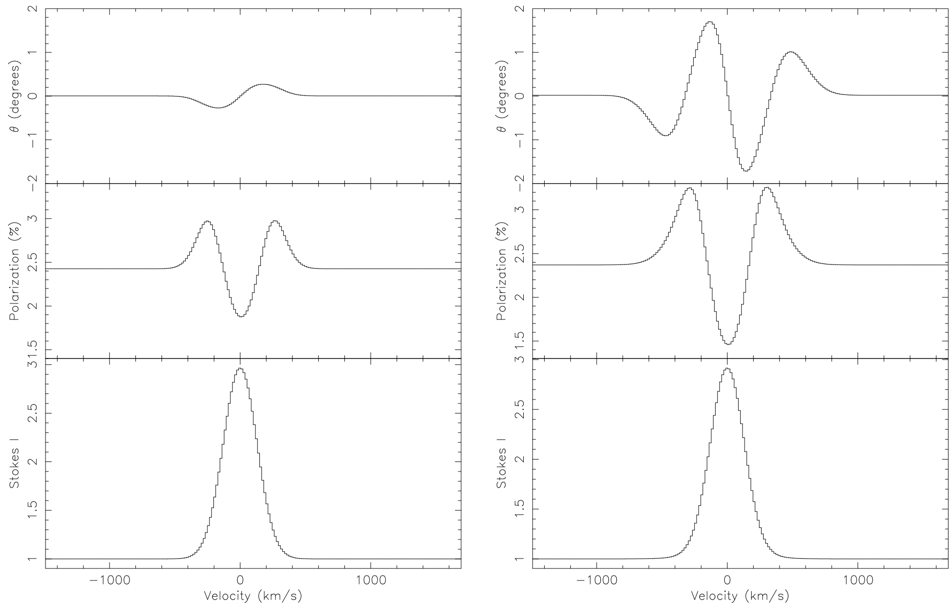

Figure 3. Monte Carlo predictions of the line polarization for the cases of a finite-sized line-emitting star embedded in a scattering disk with (left) and without (right) an inner hole. The disk is inclined at 45° and has an inner hole of 5 times the stellar radius (in the left panel).

observing with higher spectral resolution. Typical polarization spectra with a resolution of $R \simeq 9000$ of the T Tauri star RY Tau and the Herbig Ae star XY Per are presented in Figs. 1(a) and (b). The S-shaped PA flips in these data are indicative of *line* polarization, and the resulting loops in the QU plane (Fig. 2) show that a rotating disk geometry is the dominant factor in producing the line effects in the majority of Herbig Ae (9/11; Vink et al. 2002) and T Tauri stars (9/10; Vink et al. 2004, in preparation).

4. Line polarization models

Given the common occurrence of these QU loops in Herbig Ae and T Tauri stars, we are developing polarization models of line emission scattered off rotating disks. In particular, we employ the 3D Monte Carlo model TORUS (Harries 2000) to simulate both uniform as well as asymmetric illumination (by two diametrically opposed hot spots) onto a rotating scattering disk with, or without, a significant inner hole. These options of truncating the inner disk, and studying illumination via hot spots, are motivated by the growing interest in the magnetic accretion models for both T Tauri (e.g. Edwards et al. 1994), and Herbig Ae stars (e.g. Vink et al. 2002).

Figure 3 shows an intriguing result for the case of a uniformly radiating star. We find that there is a marked difference between scattering of line emission by a disk that reaches the stellar surface (Fig. 3b), and a disk with a significant inner hole (Fig. 3a). The single position-angle flip, seen on the left-hand side is similar to that predicted by the analytic models of Wood et al. (1993) – but the double

PA flip as seen on the right-hand side, associated with the undisrupted disk, is a surprise. This effect is due to the geometrically correct treatment of the finite-sized star interacting with the disk's rotational velocity field (Vink et al. 2004). Since a gradual increase of the hole size transforms the double rotations smoothly back into single ones – as the line emission object approaches that of a point source – our models demonstrate the diagnostic potential of line polarimetry in determining the disk inclination and the size of the inner hole.

By changing the configuration to a non-uniformly line emitting object, such as one where the emission originates from hot spots, we find that the line polarimetry depends strongly on the rotational phase. Stassun & Wood (1999) have shown that the magnetic accretion model can account for the observed periodic changes in the PA and polarization of continuum light. However, photopolarimetry does not provide diagnostics of the disk truncation radius. We have therefore extended Stassun & Wood type-models to spectral lines. First results indicate that there are significant changes in the shapes and amplitudes of the PA and polarization across the spectral line as a function of rotational phase.

5. Summary

We have presented data and modelling results of line polarimetry for PMS stars. For the Herbig Ae/Be stars, we found that a large majority show a line effect – indicating flattened circumstellar geometries. Interestingly, we found a marked difference between the Herbig Be stars and groups of later spectral type. For the Herbig Be stars, electron scattering disks can explain the depolarisations. At lower masses, more complex behaviour appears across Hα. Here the concept of compact line emission scattered off a rotating disk may explain the observed QU loops.

We have also presented polarimetric line profiles for scattering off accretion disks calculated with a Monte Carlo code. We considered the cases of a central object that emits line photons (a) uniformly, and (b) via hot spots only. For case (a), the switch between a point source and a finite-star photon source results in a surprising difference in the shapes of the predicted position angles. Most notably, we find double PA rotations. For case (b), emission from stellar hot spots, we find polarization signatures that are strongly dependent on hot spot phase with respect to the observer. Rotational modulation of line polarization shows great promise for unravelling the complexities occurring in the circumstellar environments around young stars.

References

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